Figure I-25 shows the mean dose to the whole body or any organ for technetium-99, carbon-14, and iodine-129, the prominent beta and photon-emitting radionuclides (DIRS 154659-BSC 2001, Volume 2, Section 4.1.4, pp. 4 to 11) for the Proposed Action inventory, higher-temperature repository operating mode, for the 1-million-year performance period. Figure I-26 shows the same information for the lower-temperature operating mode.

The data developed for the groundwater protection standard are summarized in Table I-15, which lists the peak mean gross alpha activity by scenario for various performance periods; Table I-16, which lists peak total radium concentration by scenario for various performance periods; and Table I-17, which lists the combined whole-body or organ doses in 10,000 years for the total of all beta- and photon-emitting radionuclides. The mean whole-body or organ dose was calculated by diluting the model-predicted annual activity releases of iodine-129, carbon-14, and technetium-99 [the prominent beta and photon-emitting radionuclides (DIRS 154659-BSC 2001, Volume 2, Section 4.1.4, pp. 4 to 11)] in the representative volume of groundwater (3,000 acre-feet per year). The resulting concentrations for each time step were converted to equivalent doses by scaling the appropriate dose conversion factor (4 millirem per 2,000 picocurie per liter for carbon-14; 4 millirem per 1 picocurie per liter for iodine-129; and 4 millirem per 900 picocurie for technetium 99). Calculating the sum of these three radionuclide doses for each time step produced a time history of whole-body or organ dose; the peak within 10,000 years was identified and is reported in Table I-17. This process is repeated for 95th-percentile whole-body or organ dose using model-predicted 95th-percentile annual activity releases of the prominent beta and photon-emitting radionuclides.

I.6 Waterborne Chemically Toxic Material Impacts

Several materials that are chemically toxic would be used in the construction of the repository. A screening analysis was used to determine which, if any, of these materials would have the potential to be transported to the accessible environment in quantities sufficient to be toxic to humans.

Chemicals included in the substance list for the Environmental Protection Agency's Integrated Risk Information System (DIRS 103705-EPA 1997, all; DIRS 148219, 148221, 148224, 148227, 148228, 148229, and 148233-EPA 1999, all) were evaluated to determine a concentration that would be found in drinking water in a well downgradient from the repository. The chemicals on the Integrated Risk Information System substance list that would be in the repository are barium, boron, cadmium, chromium, copper, lead, manganese, mercury, molybdenum, nickel, selenium, uranium, vanadium, and zinc.

I.6.1 SCREENING ANALYSIS

The results of the analysis of long-term performance for radionuclides detailed in Section I.5 show that, at most, three waste packages would be breached prior to 10,000 years (due to improper heat treatment) under the Proposed Action. The period of consideration for chemical toxic materials impacts was 10,000 years. Therefore, only toxic materials outside the waste package were judged to be of concern in this analysis. These are chromium, copper, manganese, molybdenum, nickel, and vanadium.

I.6.1.1 Maximum Source Concentrations of Chemically Toxic Materials in the Repository

Maximum source concentrations were calculated to provide the maximum possible concentration of that element in water entering the unsaturated zone. For materials that were not principally part of the Alloy-22 (copper and manganese), the maximum source concentration was taken to be the solubility of the material in repository water. The solubilities were obtained by modeling with the EQ3 computer code (DIRS 100836-Wolery 1992, all). The simulations were started with water from well J-13 near the Yucca Mountain site (DIRS 100814-Harrar et al. 1990, all). EQ3 calculates chemical equilibrium of a system so that, by making successive runs with gradually increasing aqueous concentrations of an element,

Table I-15. Peak mean gross alpha activity for analyzed inventories, scenarios, and temperature operating modes.[a,b]

Modeled inventory, scenario[c], and operating mode	10,000 years		100,000 years		1 million years	
	Without background	With background[d]	Without background	With background	Without background	With background
Proposed Action, nominal, higher-temperature	1.8×10^{-8}	0.40	0.017	0.42	17.7	18.1
Proposed Action, nominal, lower-temperature	3.3×10^{-8}	0.40	0.010	0.41	14.2	14.6
Inventory Module 1, nominal, higher-temperature	3.3×10^{-8}	0.40	0.023	0.42	27.7	28.1
Inventory Module 2, nominal, higher-temperature	2.2×10^{-10}	0.40	0.000042	0.40	0.039	0.44
Proposed Action, human intrusion event at 30,000 years, higher-temperature	NA[e]	NA	0.00018	0.40	0.00031	0.40

a. Adapted from DIRS 157307-BSC (2001, Enclosure 1).
b. These results are based on an annual water usage equal to 3.7 million cubic meters (exactly 3000 acre-feet) per year.
c. Mean gross alpha activity is not available for igneous activity scenarios
d. Background alpha activity concentration is 0.4 picocurie per liter.
e. NA = not applicable.

Table I-16. Peak mean total radium concentration (picocuries per liter) for analyzed inventories, scenarios, and temperature operating modes.[a,b]

Modeled inventory, scenario[c], and operating mode	10,000 years		100,000 years		1 million years	
	Without background	With background[d]	Without background	With background	Without background	With background
Proposed Action, nominal, higher-temperature	1.1×10^{-11}	1.0	2.4×10^{-5}	1.0	0.33	1.4
Proposed Action, nominal, lower-temperature	2.4×10^{-12}	1.0	2.7×10^{-5}	1.0	0.27	1.3
Inventory Module 1, nominal, higher-temperature	3.3×10^{-10}	1.0	4.0×10^{-5}	1.0	0.67	1.7
Inventory Module 2, nominal, higher-temperature	6.7×10^{-13}	1.0	6.8×10^{-9}	1.0	0.0016	1.0
Proposed Action, human intrusion event at 30,000 years, higher-temperature	NA[e]	NA	2.4×10^{-7}	1.0	3.8×10^{-7}	1.0

a. Adapted from DIRS 157307-BSC (2001, Enclosure 1).
b. These results are based on an annual water usage equal to 3.7 million cubic meters (exactly 3000 acre-feet) per year.
c. Total radium concentration is not available for igneous activity scenarios
d. Background radium activity concentration is 1.04 picocuries per liter.
e. NA = not applicable.

Table I-17. Peak mean annual whole body or organ dose (millirem)[a] for the sum of all beta- and photon-emitting radionuclides during 10,000 years after closure for analyzed inventories, scenarios, and temperature operating modes.[b]

Modeled inventory, scenario and operating mode	Total
Proposed Action, nominal, higher-temperature	2.3×10^{-5}
Proposed Action, nominal, lower-temperature	1.3×10^{-5}
Proposed Action, human intrusion event at 30,000 years, higher-temperature	NA[c]
Inventory Module 1, nominal, higher-temperature operating mode	2.8×10^{-5}

a. This represents a bounding limit (overestimate) of the maximum dose to any organ because different radionuclides would affect different organs preferentially.
b. These results are based on an annual water usage equal to 3.7 million cubic meters (exactly 3000 acre-feet) per year.
c. NA = not applicable.

eventually a result will show the saturation of a mineral in that element. That concentration at which the first mineral saturates is said to be the "solubility." The solubility of copper (from the electrical bus bars left in the tunnels) was obtained by increasing copper concentrations in successive runs of EQ3. At a concentration of 0.018 milligram per liter, copper began to precipitate as tenorite (CuO). This mineral was then in equilibrium with dissolved copper existing in approximately equal molar parts as $CuOH^+$, $Cu(CO_3)aq$, and Cu^{++}. A similar approach for manganese gave a solubility of 4.4×10^{-10} milligram per liter as pyrolusite (MnO_2) began to precipitate. In the cases of chromium, molybdenum, nickel, and vanadium, the source concentration has a potential to be very high because the corrosion of Alloy-22 could result in a very low pH solution (much different from the repository water). Thus, for purposes of screening, it was assumed that these materials had a potentially very high source concentration and should be subjected to further screening analysis (this is discussed in Section I.6.2).

I.6.1.2 Further Screening for Chemically Toxic Materials

Manganese was further analyzed using a comparison of intake to the Oral Reference Dose. The Oral Reference Dose is an indication of the limit for possible health effects from oral ingestion. Intake was based on a 2-liter (0.53-gallon) daily consumption rate of drinking water, at the maximum source concentrations (solubilities), by a 70-kilogram (154-pound) adult. Calculation takes no credit for any dilution from the source to the recipient. For manganese, the intake would be 2.2×10^{-12} milligram per kilogram per day. This is very small compared to the Oral Reference Dose of 0.14 milligram per kilogram per day listed for manganese in the Integrated Risk Information System (DIRS 148227-EPA 1997, all). Thus, it is concluded that manganese requires no further consideration.

No Oral Reference Dose is available for copper, but a similar evaluation can be made by comparing the maximum source concentration to a maximum concentration limit for the drinking water standard (40 CFR 141.2). For copper the maximum contaminant limit is 1.3 milligrams per liter. This is much higher than the source concentration of 0.018 milligram per liter, so it is concluded that copper requires no further consideration.

ORAL REFERENCE DOSE

The *Oral Reference Dose* is based on the assumption that thresholds exist for certain toxic effects such as cellular necrosis. This dose is expressed in units of milligrams per kilogram per day. In general, the oral reference dose is an estimate (with uncertainty spanning perhaps an order of magnitude) of a daily exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime (DIRS 148219-EPA 1999, all).

The remaining hazardous elements of concern (chromium, molybdenum, nickel, and vanadium) are analyzed in the next section.

I.6.2 BOUNDING CONSEQUENCE ANALYSIS FOR CHEMICALLY TOXIC MATERIALS

Further evaluation is warranted because the first level of the screening analysis (Section I.6.1) indicated that the repository could release certain waterborne chemically toxic materials into groundwater in substantial quantities and that these could represent a potential human health impact. The following materials require further evaluation: chromium, molybdenum, nickel, and vanadium. A bounding calculation for concentrations in the biosphere is presented in this section for these elements that shows the impacts would be low enough to preclude any need for more detailed fate and transport analyses.

I.6.2.1 Assumptions

The following assumptions were applied to the bounding impact analysis for waterborne chemically toxic materials:

1. The general corrosion rate of Alloy-22 is equivalent for humid-air and aqueous corrosion conditions (this assumption is consistent with treatment of this substance in the TSPA–Site Recommendation).

2. The general corrosion rate of Alloy 316NG (stainless steel) is also equivalent for humid air and aqueous corrosion conditions.

3. Consistent with Assumptions 1 and 2 above, drip shields were not assumed to effectively delay onset of general corrosion of Alloy-22 in the outer barrier layer of waste packages or the emplacement pallets.

4. Consistent with Assumptions 1, 2, and 3 above, exposed Alloy-22 and stainless steel 316NG in the drip shield rail, waste packages, and emplacement pallets would all be subject to corrosion at the same time.

5. Consistent with Assumptions 1, 2, and 3 above, all waste packages would be subject to general corrosion at the same time, and would not experience variability in the time corrosion begins.

6. The median corrosion rates for Alloy-22 and stainless steel 316NG were used in the impact estimate calculations because the rates apply to all waste packages, drip shields, and emplacement pallets in the repository.

7. A migration pathway for mobilized waterborne chemically toxic materials through the engineered barrier system to the vadose zone was assumed to exist at all times general corrosion is in progress.

8. Time delays, mitigation effects by sorption in rocks, and other beneficial effects of transport in the geosphere were neglected for purposes of this bounding impact estimate; the mass of waterborne chemically toxic materials mobilized was assumed to be instantly available at the biosphere exposure locations.

9. The concentration in groundwater was estimated by diluting the released mass of waterborne chemically toxic materials in the representative volume defined by the Environmental Protection Agency [3.7 million cubic meters (exactly 3,000 acre-feet) of water per year] in 40 CFR Part 197.

10. Under the chemical environment of the waste package, all chromium, molybdenum, nickel, and vanadium were assumed to be in their most soluble and toxic state. This is a highly conservative assumption but is consistent with other modeling of the waste package chemical environment.

11. Mobilization of chromium, molybdenum, nickel, and vanadium was assumed equivalent to the corrosion loss of stainless steel or Alloy-22 times the fraction of each element in the alloys.

12. Throughout the discussions in Section I.6.2 it is assumed that the form of mobilized chromium is the hexavalent form. The hexavalent form of chromium [Cr(VI)] is considered potentially hazardous, whereas the more common corrosion product, trivalent chromium [Cr(III)], is not. This is a conservative assumption because DOE believes that most of the mobilized Cr would be the trivalent form.

I.6.2.2 Surface Area Exposed to General Corrosion

Corrosion of the materials bearing chromium and molybdenum would occur over all exposed surface areas. The total exposed surface area of Alloy-22 surfaces (drip shield rails, outer layer of waste packages, and portions of the emplacement pallets) and stainless-steel 316NG surfaces (portions of the emplacement pallets) are calculated in this section.

Tables I-18 and I-19 summarize the calculation of the total exposed surface areas for Alloy-22 contained in the waste packages and drip shields, respectively, under the Proposed Action.

Table I-18. Total exposed surface area of the Alloy-22 outer layer of all waste packages under the Proposed Action inventory.

Waste package type[a]	Number[b]	Outer diameter[a] (millimeters)[b]	Length[a] (millimeters)[b]	Surface area[c] (square millimeters)[d]	Total surface area (square meters)[e]
21 PWR absorber plate	4,299	1,664	5,165	31,349,978	134,774
21 PWR control rods	95	1,664	5,165	31,349,978	2,978
12 PWR absorber plate	163	1,330	5,651	26,390,258	4,302
44 BWR absorber plate	2,831	1,674	5,165	31,564,675	89,360
24 BWR thick absorber plate	84	1,318	5,105	23,866,529	2,005
5 DHLW/DOE SNF	1,592	2,110	3,590	30,790,593	49,019
5 DHLW/DOE SNF–long	1,751	2,110	5,217	41,575,586	72,799
Navy SNF	200	1,949	5,430	39,214,523	7,843
Navy SNF–long	100	1,949	6,065	43,102,606	4,310
2 MCO/2 HLW	186	1,815	5,217	34,921,842	6,495
Totals	***11,301***				***373,884***

a. Waste package data from DIRS 150558-CRWMS M&O (2000, all).
b. To convert millimeters to inches, multiply by 0.0394.
c. Surface area calculated as area of a right circular cylinder.
d. To convert square millimeters to square inches, multiply by 0.00155.
e. To convert square meters to square feet, multiply by 10.764.

Table I-19. Total exposed surface area of the Alloy-22 rails for all drip shields under the Proposed Action inventory.

Component	Number of pieces	Average waste package emplacement length[a] (millimeters)[b]	Width[c] (millimeters)[d]	Thickness[c] (millimeters)	Total surface area per average waste package[e] (square millimeters[f])	Number of waste packages[c]	Total surface area for repository (square meters[g])
Rail	2	5,076	115	10	1,370,520	11,301	15,488

a. Emplacement length estimate from DIRS 155393-CRWMS M&O (2000, Attachment V, p. V-2).
b. To convert meters to feet, multiply by 3.2808.
c. Waste package data from DIRS 150558-CRWMS M&O (2000, all).
d. To convert millimeters to inches, multiply by 0.0394.
e. Surface area calculated as sum of areas of wetted surfaces (two rectangles) of angles running along the bottom of both sides of the drip shield.
f. To convert square millimeters to square inches, multiply by 0.00155.
g. To convert square meters to square feet, multiply by 10.764.

Tables I-20 and I-21 summarize the calculation of the total exposed surface areas for Alloy-22 contained in the waste packages and drip shields, respectively, for the Module 1 inventory.

Tables I-22 and I-23 summarize the calculation of the total exposed surface areas for Alloy-22 contained in the waste packages and drip shields respectively, for the Module 2 inventory.

Table I-24 summarizes the calculation of total exposed surface area for the Alloy-22 components of the emplacement pallets for the Proposed Action, Module 1, and Module 2 inventories.

Table I-20. Total exposed surface area of the Alloy-22 outer layer of all waste packages for the Module 1 inventory.

Waste package type	Number[a]	Outer diameter[a] (millimeters)[b]	Length[a] (millimeters)	Surface area[c] (square millimeters)[d]	Total surface area (square meters)[e]
21 PWR absorber plate	6,733	1,664	5,165	31,349,978	211,079
21 PWR control rods	114	1,664	5,165	31,349,978	3,574
12 PWR absorber plate	390	1,330	5,651	26,390,258	10,292
44 BWR absorber plate	4,408	1,674	5,165	31,564,675	139,137
24 BWR thick absorber plate	109	1,318	5,105	23,866,529	2,601
5 DHLW/DOE SNF	1,557	2,110	3,590	30,790,593	47,941
5 DHLW/DOE SNF–long	2,821	2,110	5,217	41,575,586	117,285
Navy SNF	200	1,949	5,430	39,214,523	7,843
Navy SNF–long	100	1,949	6,065	43,102,606	4,310
2 MCO/2 HLW	199	1,815	5,217	34,921,842	6,949
Totals	***16,631***				***551,012***

a. Waste package data from DIRS 150558-CRWMS M&O (2000, all).
b. To convert millimeters to inches, multiply by 0.0394.
c. Surface area calculated as area of a right circular cylinder.
d. To convert square millimeters to square inches, multiply by 0.00155.
e. To convert square meters to square feet, multiply by 10.764.

Table I-21. Total exposed surface area of the Alloy-22 rails for all drip shields for the Module 1 inventory.

Component	Number of pieces	Average waste package emplacement length[a] (millimeters)[b]	Width[c] (millimeters)[d]	Thickness[c] (millimeters)[d]	Total surface area per average waste package[e] (square millimeters)[f]	Number of waste packages[c]	Total surface area for repository (square meters)[g]
Rail	2	5,076	115	10	1,370,520	16.631	22,793

a. Emplacement length estimate from DIRS 155393-CRWMS M&O (2000, Attachment V, p. V-2).
b. To convert meters to feet, multiply by 3.2808.
c. Waste package data from DIRS 150558-CRWMS M&O (2000, all).
d. To convert millimeters to inches, multiply by 0.0394.
e. Surface area calculated as sum of areas of wetted surfaces (two rectangles) of angles running along the bottom of both sides of the drip shield.
f. To convert square millimeters to square inches, multiply by 0.00155.
g. To convert square meters to square feet, multiply by 10.764.

Table I-22. Total exposed surface area of the Alloy-22 outer layer of all waste packages for the Module 2 inventory.

Waste package type	Number[a]	Outer diameter[a] (millimeters[b])	Length[a] (millimeters[b])	Surface area[c] (square millimeters[d])	Total surface area (square meters[e])
21 PWR absorber plate	6,733	1,664	5,165	31,349,978	211,079
21 PWR control rods	114	1,664	5,165	31,349,978	3,574
12 PWR absorber plate	390	1,330	5,651	26,390,258	10,292
44 BWR absorber plate	4,408	1,674	5,165	31,564,675	139,137
24 BWR thick absorber plate	109	1,318	5,105	23,866,529	2,601
5 DHLW/DOE SNF	1,557	2,110	3,590	30,790,593	47,941
5 DHLW/DOE SNF–long	2,821	2,110	5,217	41,575,586	117,285
Navy SNF	200	1,949	5,430	39,214,523	7,843
Navy SNF–long	100	1,949	6,065	43,102,606	4,310
Navy–long (GTCC and SPAR)[f]	601	1,949	6,065	43,102,606	25,905
2 MCO/2 DHLW	199	1,815	5,217	34,921,842	6,949
Totals	***17,232***				***576,917***

a. Waste package data from DIRS 150558-CRWMS M&O (2000, all).
b. To convert millimeters to inches, multiply by 0.0394.
c. Surface area calculated as area of a right circular cylinder.
d. To convert square millimeters to square inches, multiply by 0.00155.
e. To convert square meters to square feet, multiply by 10.764.
f. Navy SNF-long type waste packages used to represent disposal of Greater-Than-Class-C (GTCC) and Special-Performance-Assessment-Required (SPAR) waste.

Table I-23. Total exposed surface area of the Alloy-22 rails for all drip shields for the Module 2 inventory.

Component	Number of pieces	Average waste package emplacement length[a] (millimeters)[b]	Width[c] (millimeters)[d]	Thickness[c] (millimeters)[d]	Total surface area per average waste package[e] (square millimeters)[f]	Number of waste packages[c]	Total surface area for repository (square meters)[g]
Rail	2	5,076	115	10	1,370,520	17,232	23,617

a. Emplacement length estimate from DIRS 155393-CRWMS M&O (2000, Attachment V, p. V-2).
b. To convert meters to feet, multiply by 3.2808.
c. Waste package data from DIRS 150558-CRWMS M&O (2000, all).
d. To convert millimeters to inches, multiply by 0.0394.
e. Surface area calculated as sum of areas of wetted surfaces (two rectangles) of angles running along the bottom of both sides of the drip shield.
f. To convert square millimeters to square inches, multiply by 0.00155.
g. To convert square meters to square feet, multiply by 10.764.

Table I-24. Total exposed surface area of the Alloy-22 components for all emplacement pallets under the Proposed Action, Module 1, and Module 2 inventories.

Emplacement pallet component[a]	Number of pieces[a]	Length[a] (millimeters)[b]	Width[a] (millimeters)	Number of sides[a]	Total surface area per pallet (square meters)[c]	Number of pallets[d]	Total surface area repository (square meters)[c]
Plate 1	2	1,845	552.4	1	4.077[e]		
Plate 2	2	922.5	614	2	2.266[f]		
Plate 3	2				2.219[g]		
Plate 4	4	552	462	2	2.040[h]		
Plate 5	4	552	80	2	0.353[i]		
Plate 6	4	1,266.7	603.2	2	6.113[j]		
Plate 7	4	152.4	79.9	2	0.049[k]		
Plate 8	4	152.4	552.4	1	0.337[l]		
Totals for Proposed Action					***17.45***	***11,301***	***197,240***
Totals for Inventory Module 1					***17.45***	***16,631***	***290,266***
Totals for Inventory Module 2					***17.45***	***17,232***	***300,756***

a. Emplacement pallet details from sketches SK-0189 Rev 0 and SK-0144 Rev 1, DIRS 150558-CRWMS M&O (2000).
b. To convert millimeters to inches, multiply by 0.0394.
c. To convert square meters to square feet, multiply by 10.764.
d. Waste package data from DIRS 150558-CRWMS M&O (2000, all).
e. Calculated for one wetted rectangular side.
f. Calculated for both wetted rectangular sides.
g. Surface area equal to that of Plate 2 less area covered by 5.1-centimeter (2.0-inch) tube cross-sections.
h. Calculated assuming rectangular area covered by tubes is not wetted; note that while the inside and outside are covered by tubes the width dimension is correct for each side.
i. Calculated assuming rectangular wetted area.
j. Calculated assuming wetted area includes exposed edge thicknesses which are added to the length and width
k. Calculated based on triangular area.
l. Calculated assuming one wetted side only (because it is covered by the tube).

The sum of exposed total surface areas for waste packages, drip shield rails, and emplacement pallet components fabricated from Alloy-22 (from Tables I-18, I-19, and I-24) is 586,612 square meters (6,314,240 square feet) under the Proposed Action. For Inventory Module 1, the sum of exposed total surface areas (from Tables I-20, I-21, and I-24) is 864,072 square meters (9,300,794 square feet). For Inventory Module 2, the sum of exposed total surface areas (from Tables I-22, I-23, and I-24) is 901,290 square meters (9,701,400 square feet). This is the area of Alloy-22 subject to generalized corrosion under the assumptions outlined for this bounding impact estimate.

Tables I-25, I-26, and I-27 summarize the calculation of the total exposed surface areas for stainless steel 316NG used in the emplacement pallets for the Proposed Action, Module 1, and Module 2 inventories, respectively.

Table I-25. Total exposed surface area of the stainless-steel 316NG components for all emplacement pallets under the Proposed Action inventory.

Emplacement pallet tubes	Number of pieces[a]	Length[a] (millimeters[b])	Width[a] (millimeters)	Number of sides[a]	Total surface area per average waste package[c] (square meters[d])	Number of waste packages[e,f]	Total surface area repository (square meters)
Long pallets	4	4,147	609.6	2	18.877[f]	9,709	183,278
Short pallets	4	2,500	609.6	2	10.845[g]	1,592	17,265
Totals						***11,301***	***200,543***

a. Emplacement pallet details from sketches SK-0189 Rev 0 and SK-0144 Rev 1 (DIRS 150558-CRWMS M&O 2000).
b. To convert millimeters to inches, multiply by 0.0394.
c. Calculated for area of all wetted rectangular sides.
d. To convert square meters to square feet, multiply by 10.764.
e. Waste package data from DIRS 150558-CRWMS M&O (2000, all).
f. Only waste packages of type "5 DHLW/DOE SNF" are assumed to utilize short pallets.

Table I-26. Total exposed surface area of the stainless-steel 316NG components for all emplacement pallets for the Module 1 inventory.

Emplacement pallet tubes	Number of pieces[a]	Length[a] (millimeters[b])	Width[a] (millimeters)	Number of sides[a]	Total surface area per average waste package[c] (square meters[d])	Number of waste packages[e,f]	Total surface area repository (square meters)
Long pallets	4	4,147	609.6	2	18.877[f]	15,075	284,533
Short pallets	4	2,500	609.6	2	10.845[g]	1,557	16,886
Totals						***16,632***	***301,419***

a. Emplacement pallet details from sketches SK-0189 Rev 0 and SK-0144 Rev 1 (DIRS 150558-CRWMS M&O 2000).
b. To convert millimeters to inches, multiply by 0.0394.
c. Calculated for area of all wetted rectangular sides.
d. To convert square meters to square feet, multiply by 10.764.
e. Waste package data from DIRS 150558-CRWMS M&O (2000, all).
f. Only waste packages of type "5 DHLW/DOE SNF" are assumed to utilize short pallets.

Table I-27. Total exposed surface area of the stainless-steel 316NG components for all emplacement pallets for the Module 2 inventory.

Emplacement pallet tubes	Number of pieces[a]	Length[a] (millimeters[b])	Width[a] (millimeters)	Number of sides[a]	Total surface area per average waste package[c] (square meters[d])	Number of waste packages[e,f]	Total surface area repository (square meters)
Long pallets	4	4,147	609.6	2	18.877[f]	15,675	295,899
Short pallets	4	2,500	609.6	2	10.845[g]	1,557	16,886
Totals						***17,232***	***312,785***

a. Emplacement pallet details from sketches SK-0189 Rev 0 and SK-0144 Rev 1 (DIRS 150558-CRWMS M&O 2000).
b. To convert millimeters to inches, multiply by 0.0394.
c. Calculated for area of all wetted rectangular sides.
d. To convert square meters to square feet, multiply by 10.764.
e. Waste package data from DIRS 150558-CRWMS M&O (2000, all).
f. Only waste packages of type "5 DHLW/DOE SNF" are assumed to utilize short pallets.

I.6.2.3 General Corrosion Rates

The general corrosion rate for Alloy-22 has been measured in laboratory experiments. The corrosion rate was input to the TSPA model as a cumulative distribution function. The 5th percentile is 0.000012 millimeter (0.0000004 inch) per year, the median value is 0.000045 millimeter (0.0000017 inch) per year, and the 95th-percentile of the distribution is 0.00008 millimeter (0.000003 inch) per year (DIRS 152542-CRWMS M&O 2000, Figure 1, p. 11). For purposes of this bounding calculation, the median rate was chosen because the calculation is concerned with the average rate of corrosion over a large number of waste packages, drip shield rails, and emplacement pallets. Hence, the median rate is representative of repository conditions taken as a whole over the 10,000-year post-closure period.

The median general corrosion rate for stainless steel 316NG is 0.01 micron per year (0.0000394 inch per year) (DIRS 135968-CRWMS M&O 2000, Figure 3-15, p. 3-30).

I.6.2.4 Release Rates

The rate of release of waterborne chemically toxic materials was calculated as the product of the surface area exposed to general corrosion, the general corrosion rate, and the weight fraction of the alloy for the waterborne chemically toxic material of interest. Alloy-22 is comprised of among other elements, 22.5 percent (maximum) chromium, 14.5 percent (maximum) molybdenum, 57.2 percent nickel, and 0.35 percent vanadium (DIRS 104328-ASTM 1998, all). Stainless steel 316NG is assumed to be essentially the same as 316L, which is comprised, among other elements, of 17.0 percent chromium, 12 percent nickel, and 2.5 percent molybdenum with no vanadium (DIRS 102933-CRWMS M&O 1999, p. 13).

Tables I-28, I-29, and I-30 summarize the calculation of the bounding mass release rates for the Proposed Action, Module 1, and Module 2 inventories, respectively. The mass release rates for chromium, molybdenum, nickel, and vanadium are based on the surface exposure area of exposed repository components containing these elements, the general corrosion rates for those components, and the weight percent content of the individual elements.

Table I-28. Bounding mass release rates (grams per year)[a] from Alloy-22 and stainless-steel 316NG components from general corrosion for the Proposed Action.

Alloy	Total exposed surface area in repository (square meters)[b]	General corrosion rate (meters per year)[c]	Alloy release volume (cubic meter per year)[d]	Alloy density (grams per cubic meter)[e]	Bounding mass release rate (grams per year)[a]				
					Alloy	Chromium	Molybdenum	Nickel	Vanadium
Alloy-22	586,612	4.5×10^{-8}	0.0264	8,690,000	229,395	51,614	33,262	131,099	803
316NG	200,543	1.0×10^{-8}	0.00201	7,980,000	16,003	2,721	400	1,920	0
Totals						***54,334***	***33,662***	***133,019***	***803***

a. To convert grams to ounces, multiply by 0.035273.
b. To convert square meters to square feet, multiply by 10.764.
c. To convert meters to feet, multiply by 3.2468.
d. To convert cubic meters to cubic feet, multiply by 35.314.
e. To convert grams per cubic meter to ounces per cubic foot, multiply by 0.0010047.

Table I-29. Bounding mass release rates (grams per year)[a] from Alloy-22 and stainless-steel 316NG components from general corrosion for Module 1.

Alloy	Total exposed surface area in repository (square meters)[b]	General corrosion rate (meters per year)[c]	Alloy release volume (cubic meter per year)[d]	Alloy density (grams per cubic meter)[e]	Bounding mass release rate (grams per year)[a]				
					Alloy	Chromium	Molybdenum	Nickel	Vanadium
Alloy-22	864,072	4.5×10^{-8}	0.0389	8,690,000	337,895	76,026	48,995	193,107	1,183
316NG	312,785	1.0×10^{-8}	0.0030	7,980,000	24,055	4,089	601	2,887	0
Totals						***80,116***	***49,596***	***195,994***	***1,183***

a. To convert grams to ounces, multiply by 0.035273.
b. To convert square meters to square feet, multiply by 10.764.
c. To convert meters to feet, multiply by 3.2468.
d. To convert cubic meters to cubic feet, multiply by 35.314.
e. To convert grams per cubic meter to ounces per cubic foot, multiply by 0.0010047.

I.6.2.5 Summary of Bounding Impacts

The bounding maximum concentration is based on the general corrosion rate of the source materials and the representative volume for dilution prescribed in the final Environmental Protection Agency regulation 40 CFR Part 197. Diluting the bounding release rates presented in Section I.6.2.4 for chromium, molybdenum, nickel, and vanadium in the prescribed representative volume of water (3.7 million cubic meters, or exactly 3,000 acre-feet per year) used for calculation of groundwater protection impacts for

Table I-30. Bounding mass release rates (grams per year)[a] from Alloy-22 and stainless-steel 316NG components from general corrosion for Module 2.

Alloy	Total exposed surface area in reposritoy (square meters)[b]	General corrosion rate (meters per year)[c]	Alloy release volume (cubic meter per year)[d]	Alloy density (grams per cubic meter)[e]	Bounding mass release rate (grams per year)[a]				
					Alloy	Chromium	Molybdenum	Nickel	Vanadium
Alloy-22	901,290	4.5×10^{-8}	0.0406	8,690,000	352,450	79,301	51,105	201,425	1,233
316NG	312,785	1.0×10^{-8}	0.0031	7,980,000	24,960	4,243	624	2,995	0
Totals						***83,544***	***51,729***	***204,420***	***1,233***

a. To convert grams to ounces, multiply by 0.035273.
b. To convert square meters to square feet, multiply by 10.764.
c. To convert meters to feet, multiply by 3.2468.
d. To convert cubic meters to cubic feet, multiply by 35.314.
e. To convert grams per cubic meter to ounces per cubic foot, multiply by 0.0010047.

waterborne radioactive materials results in the bounding concentration in groundwater at exposure locations for these chemically toxic materials listed in Table I-31.

Table I-31. Bounding concentrations of waterborne chemical materials of concern compared to Maximum Contaminant Levels Goals (milligrams per liter).

Material	Maximum Contaminant Level Goal	Maximum bounding concentration		
		Proposed Action	Inventory Module 1	Inventory Module 2
Chromium (VI)	0.1[a]	0.015	0.022	0.023
Molybdenum	NA[b]	0.009	0.013	0.014
Nickel	NA	0.036	0.053	0.055
Vanadium	NA	0.00022	0.00032	0.00033

a. 40 CFR 141.51.
b. NA = not available.

There are two measures for comparing human health effects for chromium. When the Environmental Protection Agency established its Maximum Contaminant Level Goals, it considered safe levels of contaminants in drinking water and the ability to achieve these levels with the best available technology. The Maximum Contaminant Level Goal for chromium is 0.1 milligram per liter (40 CFR 141.51). The bounding concentrations for the Proposed Action and for Inventory Modules 1 and 2 (Table I-31) are well below the Maximum Contaminant Level Goal for chromium. The other measure for comparison is the Oral Reference Dose for chromium, which is 0.005 milligram per kilogram of body mass per day (DIRS 148224-EPA 1999, all). The reference dose factor represents a level of intake that has no adverse effect on humans. It can be converted to a threshold concentration level for drinking water. The conversion yields essentially the same concentration for the reference dose factor as the Maximum Contaminant Level Goal.

No attempt can be made at present to express the bounding estimate of groundwater concentration of hexavalent chromium in terms of human health effects (for example, latent cancer fatalities). The carcinogenicity of hexavalent chromium by the oral route of exposure cannot be determined because of a lack of sufficient epidemiological or toxicological data (DIRS 148224-EPA 1999, all; DIRS 101825-EPA 1998, p. 48).

There is no Maximum Contaminant Level Goals for molybdenum, nickel, or vanadium. However, we can compare the intake based on the maximum bounding concentrations in Table I-31 to the Oral Reference Dose for each of these materials. The intakes by chemical, assuming water consumption of 2 liters (0.53 gallon) per day by a 70-kilogram (154-pound) person, are listed in Table I-32 along with the relevant Oral Reference Dose. The values in Table I-32 show that the intakes are well below the respective Oral Reference Doses for chromium, molybdenum, nickel, and vanadium for the Proposed Action, Inventory Modules 1, and Inventory Module 2.

Table I-32. Summary of intake of waterborne chemical materials of concern based on maximum bounding concentrations listed in Table I-31 compared to Oral Reference Doses.

Material	Oral Reference Dose	Intake[a]		
		Proposed Action	Inventory Module 1	Inventory Module 2
Chromium (VI)	0.005[b]	0.00042	0.00062	0.00065
Molybdenum	0.005[c]	0.00026	0.00038	0.00040
Nickel	0.02[d]	0.0010	0.0015	0.0016
Vanadium	0.007[e]	0.0000062	0.0000091	0.000010

a. Assuming daily intake of 2.0 liters (0.53 gallon) per day by a 70-kilogram (154-pound) individual.
b. DIRS 148224-EPA 1999, all.
c. DIRS 148228-EPA 1999, all.
d. DIRS 148229-EPA 1999, all.
e. DIRS 103705-EPA 1997, all.

Because the bounding concentration of chromium, molybdenum, nickel, and vanadium in groundwater is calculated to be below the Maximum Contaminant Level Goal or yield intakes well below the respective Oral Reference Doses, there is no further need to refine the calculation to account for physical processes that would limit mobilization of these materials or delay and dilute them during transport in the geosphere.

I.7 Atmospheric Radioactive Material Impacts

Following closure of the proposed Yucca Mountain Repository, there would be limited potential for releases to the atmosphere because the waste would be isolated far below the ground surface. Still, the rock is porous and does allow gas to flow, so the analysis must consider possible airborne releases. The only radionuclide that would have a relatively large inventory and a potential for gas transport is carbon-14. Iodine-129 can exist in a gas phase, but it is highly soluble and, therefore, would be more likely to dissolve in groundwater rather than migrate as a gas. Other gas-phase isotopes were eliminated in the screening analysis (Section I.3.3), usually because they have short half-lives and are not decay products of long-lived isotopes. A separate screening argument for radon-222 is provided in Section I.7.3. After carbon-14 escaped from the waste package, it could flow through the rock in the form of carbon dioxide. Atmospheric pathway models were used to estimate human health impacts to the local population in the 80-kilometer (50-mile) region surrounding the repository.

About 2 percent of the carbon-14 in commercial spent nuclear fuel exists as a gas in the space (or *gap*) between the fuel and the cladding around the fuel (DIRS 103446-Oversby 1987, p. 92). The average carbon-14 inventory in a commercial spent nuclear fuel waste package is approximately 1.37 grams (0.048 ounce) (6.11 curies) (see Table I-5), so the analysis used a gas-phase inventory of 0.122 curie of carbon-14 per commercial spent nuclear fuel waste package to calculate impacts from the atmospheric release pathway. The waterborne radioactive materials analysis described in Chapter 5, Section 5.4 included the entire inventory of the carbon-14 in the repository in the groundwater release models. Thus, the groundwater-based impacts would be overestimated slightly (by 2 percent) by this modeling approach.

Carbon is the second-most abundant element (by mass) in the human body, constituting 23 percent of Reference Man (DIRS 101074-ICRP 1975, p. 327). Ninety-nine percent of the carbon comes from food ingestion (DIRS 148066-Killough and Rohwer 1978, p. 141). Daily carbon intakes are approximately 300 grams (0.7 pound) and losses include 270 grams (0.6 pound) exhaled, 7 grams (0.02 pound) in feces, and 5 grams (0.01 pound) in urine (DIRS 101074-ICRP 1975, p. 377).

Carbon-14 dosimetry can be performed assuming specific-activity equivalence. The primary human intake pathway of carbon is food ingestion. The carbon-14 in food results from photosynthetic processing of atmospheric carbon dioxide, whether the food is the plant itself or an animal that feeds on